ELECTRO-OPTIC SURFACE FIELD IMAGING SYSTEM

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The use of photoconductive semiconductor switches in pulsed-power applications has become more popular in recent years. These switches are useful primarily for two reasons: speed and high voltage capability. The simultaneous requirements of speed and high voltage can place narrow constraints on photoconductive switch contact design. For high speed, switch contacts must be narrowly spaced. To hold off high voltage, contacts must be more widely spaced. Optimizing for speed and voltage requirements results in significant electric fields between switch electrodes. Pulsed power switches may have relatively large contact separations, but are required to hold off very large voltages. Field strengths of 100 kV/cm between contacts are typical. Surface breakdown is the limiting factor in the operation of such switches, as high voltage switches will break down preferentially along the surface between the electrodes. The need to keep surface electric fields below the threshold where surface breakdown will occur places a limit on the maximum voltage at which a switch can operate.

The mechanism of surface breakdown in semiconductors is poorly understood. A better understanding of the surface electric field between switch contacts would be very useful in the study of surface breakdown. An understanding of the surface electric field above semiconductor switches is complicated by the presence of free carriers below the surface. Measurement of the interelectrode field is made more difficult as the field probe must be placed in a high field environment. Any form of metallic contact probe cannot be used. Also, high-speed switches require a field probe with ultrafast temporal response to monitor the transient surface electric fields present during switch operation. The electro-optic, or Pockel's effect, provides an extremely useful probe of surface electric fields. Using the electro-optic effect, surface fields can be measured with an optical probe. This paper describes an electro-optic probe which is used to provide an optical image of the electric field between metallic contacts on semiconductor surfaces and monitor the temporal evolution of this field. The probe provides two-dimensional images of the electric field in real time and has picosecond time response.

The electro-optic, or Pockel's effect, is the phenomena whereby the birefringence of certain crystals can be altered by an electric field applied across the crystal. Such crystals are termed "electro-optic" crystals. The change in these crystal's birefringence can be measured by probing the crystal with polarized light. As the polarized probe beam transverses the crystal, the crystal birefringence rotates the probe beam's polarization. The Pockel's effect can be viewed as the mixing of an optical field and an electric field inside the crystal to produce a new optical field with its polarization rotated with respect to the original optical field. This rotation can be detected and be used as a measure of the electric field present in the crystal at the point where the probe beam transversed the crystal. To produce the desired effect, the crystal axis, optical polarization, and electric field must all be aligned properly. This alignment depends on the particular electro-optic crystal used [1]. Physically, the mechanism responsible for the Pockel's effect, electric polarizability, is a femtosecond regime process. This allows for an extremely short response time to applied electric fields, with a bandwidth limited to about 1 THz due to crystal absorption. By coupling electro-optic sampling with short-pulse lasers, an ultrafast, non-contacting probe field probe is obtained. Subpicosecond electrical signals have been characterized electro-optically [2]. Details of the probe beam, electrodes, and crystal geometry for the surface field probe are shown in Fig. 1.

Figure 1 shows the surface field probe set up to measure the field on a typical photoconductive switch. The switch to be monitored has two rectangular metallic contact pads on a semiconductor substrate. When a bias voltage is applied to the metallic contacts, an electric field is established between the contacts. There is a fringing field which extends above the surface of the semiconductor substrate. The electro-optic crystal is placed directly on top of the switch, covering the contact gap completely. A dielectric mirror is bonded to the underside of the crystal. This reflection coated side is in contact with the semiconductor substrate. The crystal is immersed in the fringing electric field between the contacts. The birefringence of the crystal is altered by this

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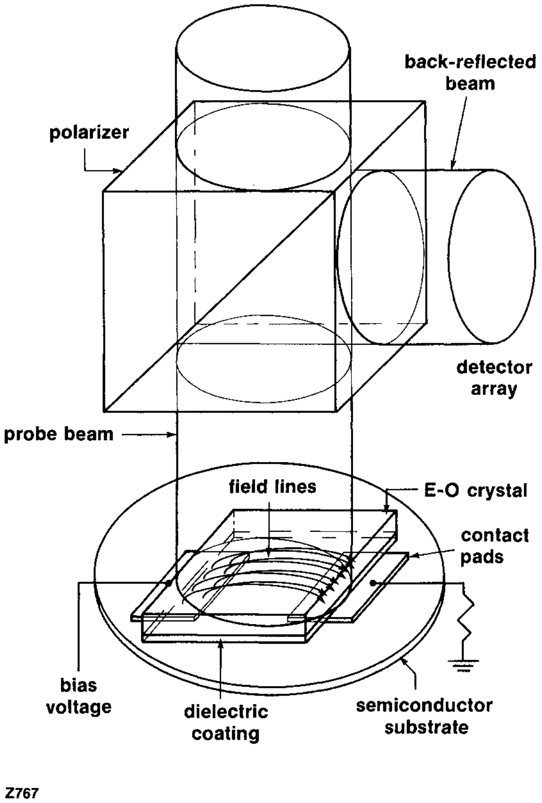

Fig. 1 Details of the electro-optic probe.

field. The optical probe beam is polarized and directed onto the crystal and test substrate. The beam diameter is greater than the contact gap so that the entire contact gap is illuminated. The beam transverses the crystal and is reflected back onto itself by the dielectric mirror on the substrate side of the crystal. While the beam is in the crystal, the optical field and electric field mix so that the polarization of the back-reflected beam is altered with respect to the incoming beam. Any component of the back-reflected with polarization different from the incoming beam will be rejected by the polarizer. Each point in the cross section of the rejected beam has sampled the local birefringence of the corresponding point in the crystal. The back-reflected beam, thus, contains information about the electric field at each point in the crystal encoded in the polarization, and, therefore, is an optical replica of the electric field. The rejected beam is imaged onto a two-dimensional diode array so that the field information can be extracted. As the optical probe beam makes a double pass through the polarizer, the crystal can be considered to be between two crossed polarizers. The intensity at any given point in the cross-section of the rejected beam will depend on the sine squared of the polarization rotation that particular beam element experienced in the crystal. The transmission to the detector can be written [1]:

$$T = \sin^2 \left\{ [(KEd) + \phi]/2 \right\} \qquad (1)$$

where E is the magnitude of the dc electric field, d is the optical path length through the crystal, ϕ is a constant optical rotation due to static birefringence in the crystal and any wave plate used, and K is a constant that depends on material parameters and the frequency of the optical field. To obtain the best response to the applied electric field, a quarter-wave plate is placed between the polarizer and the crystal to optically bias the probe beam at the quasi-linear portion of the $\sin^2$ transmission curve.

For the experiments conducted to date, the switch consisted of gold contacts on a silicon substrate. The contacts were vapor deposited after the substrate was cleaned with an HFl acid wash. The contacts were annealed by baking the substrate at 450°C for one-half hour. The contacts were shown to be ohmic to 1500 V. The contact gap was 3 mm. The electro-optic crystal used was $LiTaO_3$. The $LiTaO_3$ was 1 cm^2 and 0.5 mm thick. The top surface of the $LiTaO_3$ was antireflection coated to prevent internal reflection and improve transmission through the crystal. The crystal axis was perpendicular to the contact edges and parallel to the electric field. In this geometry, the crystal is sensitive only to the electric field component along the $LiTaO_3$ crystal axis.

The complete probe system is shown in Fig. 2. The entire system consists of the test switch and crystal shown in detail in Fig. 1, detector array, high-voltage pulser, optical delay translation stage, and infrared and visible laser beams. The entire system is computer controlled.

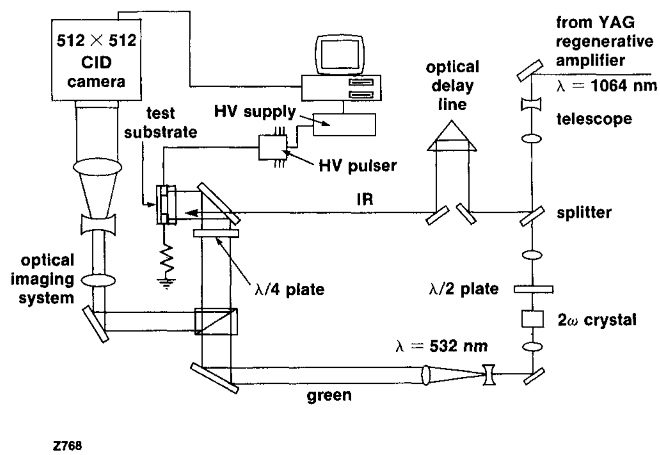

Fig. 2 Overall probe system layout.

The laser source is a Nd:YAG regenerative amplifier seeded by a Nd:YAG mode-locked oscillator. Wavelength is 1064 nm and pulse width is nominally 100 ps. The amplifier output is typically 350 μJ per pulse. The pulse repetition rate is variable up to 1 kHz. The infrared beam from the amplifier is first collimated and then split,

90% for switching use and 10% for second harmonic generation. Green (λ = 532 nm) laser pulses are generated in a KTP crystal. This green beam is upcollimated and serves as the probe beam. Green beam diameter is 1.25 cm, which will completely illuminate the 1 cm^2 $LiTaO_3$ crystal. The back-reflected green probe pulses are imaged onto a 512 x 512 element CID camera array. The CID camera is interfaced to the computer supplying a digital image of the modulated probe beam. Individual frames from the camera can be acquired. As the green probe consists of 100 ps pulses, the switch surface field is only sampled during a 100 ps window in time. In effect, a "snapshot" of the electric field is taken with a 100 ps strobe. The temporal evolution of the surface electric field can be monitored by sweeping the 100 ps probe pulse window past a transient event, or, alternatively, sweeping the transient event past the probe window. This last process is what is done in the current experiments. The infrared switching beam is sent through an optical delay line consisting of a retro-reflector on a translation stage. The infrared pulse is directed onto the switch collinear with the green probe pulse. The infrared pulse passes through the dielectric mirror on the $LiTaO_3$ (coated for 532 nm) to photoconductively switch the silicon substrate. By appropriately timing the arrival of the green and infrared pulses at the test switch, the surface electric field during switching can be monitored. The green probe pulse does not switch the silicon as it is reflected by the dielectric mirror on the crystal. This is essentially a "pump-probe" experiment.

For the probe to operate in real time, the field data must be collected with a single laser pulse. This is essential to capture unique events like surface breakdown where the switch can be destroyed after one event. To insure that the CID camera sees only one laser pulse, the camera and the laser system are synchronized to the same electronic oscillator. Data is taken at a 30 Hz repetition rate, limited by the camera.

To extract the field data from the camera image, a frame is first acquired with the high voltage bias on and then with the bias off. The bias is applied with a computer-controlled pulser, variable voltage from 0-10 kV. The two frames (each pixel within each frame) represent two different points on the transmission curve given earlier [Eq. (1)]. Each image is digitized with 8-bit resolution, scaled, and reduced to an 32 x 32 array. These two arrays, voltage on and voltage off, are used as inputs to a function which transforms the raw optical images to a map of the electric field. The resulting map has an 8-bit range and can be displayed as a false-color image on a monitor or the digital image can be manipulated to produce field contour plots, axonometric plots, or field cross sections at a particular line across the switch. Spatial resolution is under 10 μm. The probe is sensitive to field strengths of 0.1 kV/cm .

Figures 3 and 4 show typical data acquired with the field probe. Figure 3 is an axonometric plot of the surface field across the 3 cm gap silicon switch acquired with a single laser pulse. The switch bias was 5 kV giving a field strength of 17 kV/cm. The data has been scaled to the range 0-255 by the computer. The scale is such that a value of 128 represents no change between images taken with bias on and bias off, and, hence, no electric field perpendicular to the contacts. The collinear infrared had been blocked, so that Fig. 3 is a map of the dc field produced by the high voltage pulser. Note there is no field measured over the contacts themselves. This is consistent, as the electric field over the contacts would be vertical, i.e., perpendicular to the substrate, and the crystal is not sensitive to this field orientation.

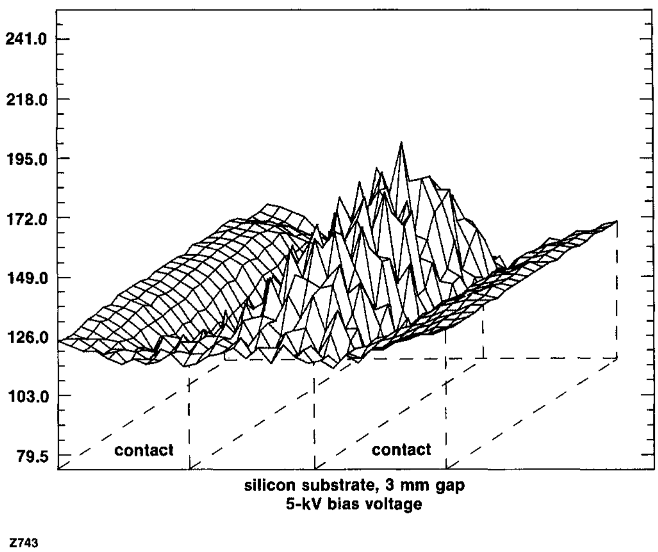

Fig. 3 Surface field map obtained with electro-optic probe system.

Figure 4 displays the temporal evolution of the surface field across the 3-mm gap silicon switch. Each graph is a cross section of the field, taken through the center of the contacts. Two data runs are averaged to produce each graph, reducing noise. Switch bias was 5.8 kV. The infrared switching pulse was swept past the green probe pulse in 50 ps steps. Graphs are shown for each 100 ps. The surface electric field collapses at the onset of photoconductive switching. The field collapses within 300 ps, which is consistent with the 100 ps pulse width of the laser. Figure 4 illustrates the ability of the system to monitor the field during photoconductive switching.

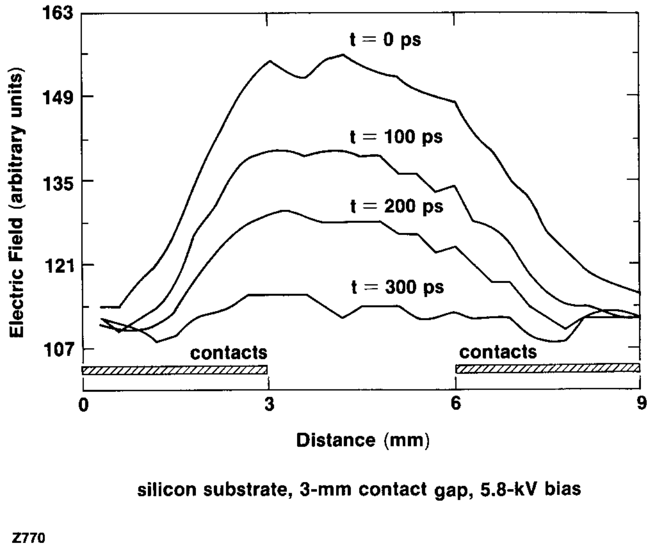

Fig. 4 Temporal evolution of surface field of switch during photoconductive switching.

Other experiments done to date include monitoring carrier migration with the surface field probe. This was done by directing the infrared switching beam onto an area close to one contact, instead of illuminating the contact gap uniformly. This creates carriers near one contact, which will then migrate to the other contact. Carriers created at one contact will take a finite time to transit the gap and reach the other contact. For the 3 mm gap used, this time is approximately 30 ns. This leads to a lop-sided distribution of carriers across the gap in space and time. The surface field is influenced by the presence of carriers in the gap. Figure 4 shows how the uniform illumination of the gap, and, hence, uniform creation of carriers collapses the surface field uniformly. The nonuniform creation of carriers from spot illumination near one contact nonuniformly collapses the surface field. The temporal evolution of this nonuniform field collapse has been monitored with the field probe. The progressive collapse of the surface field is a measure of the carrier migration.

The demonstrated ability of this novel probe to map surface electric fields on a picosecond time scale makes it a valuable tool in the study of photoconductive switch physics. Its primary strength lies in its capability of monitoring events in the switch gap itself. This is a distinct advantage over monitoring only the switched output waveform. Maps of the surface field within the electrode gap could serve as tests of computer models of photoconductive switching. The surface field could also be used as diagnostic for investigating the dynamics of carriers within the contact gap. Surface field measurements could be tied in with simulations to produce a coherent model of carrier behavior. Surface field maps could also be useful in characterizing different electrode shapes and designs. While the probe was developed for pulsed power applications, it could be used for mapping the electric field of metallic contacts of other devices. For example, in integrated circuit design voltages are low but contacts are very closely spaced, resulting in high field situations. This probe could be useful in mapping the electric field of LSI circuit contacts.

Future work will center around improving the system spatial resolution and voltage sensitivity and calibrating the electric field measurements. The probe will then be used in the study of carrier physics within the switch gap and in the study of surface breakdown.

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